# Seeing is Believing:
# Telescopes on Earth and in Space

Donna Kubik Museum of Natural History Nov. 9, 2008

# 2000 objects

- About 2000 celestial objects are visible to the naked eye
  - The Sun
  - Moon
  - 5 planets
  - Bright stars

# Hundreds of millions of objects

- Yet astronomers have cataloged literally hundreds of millions of celestial objects!

Hubble Deep Field

# Seeing is Believing:

- What limits how much the naked eye can see?
  - Small aperture
  - Short integration time
  - Narrow bandwidth

# Telescopes on Earth and in Space

- How have astronomers overcome the limitations imposed by the human eye?
  - Telescopes
  - Cameras
  - Telescopes and cameras that can detect colors beyond those the eye can see

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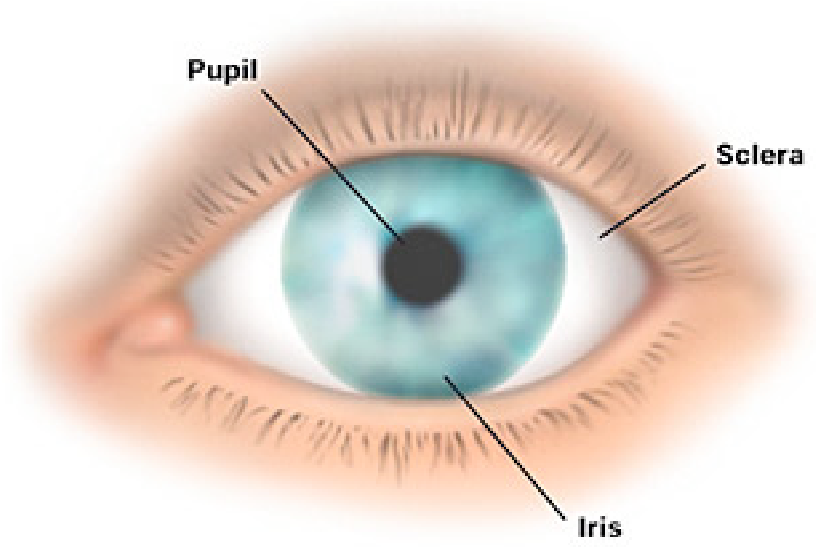
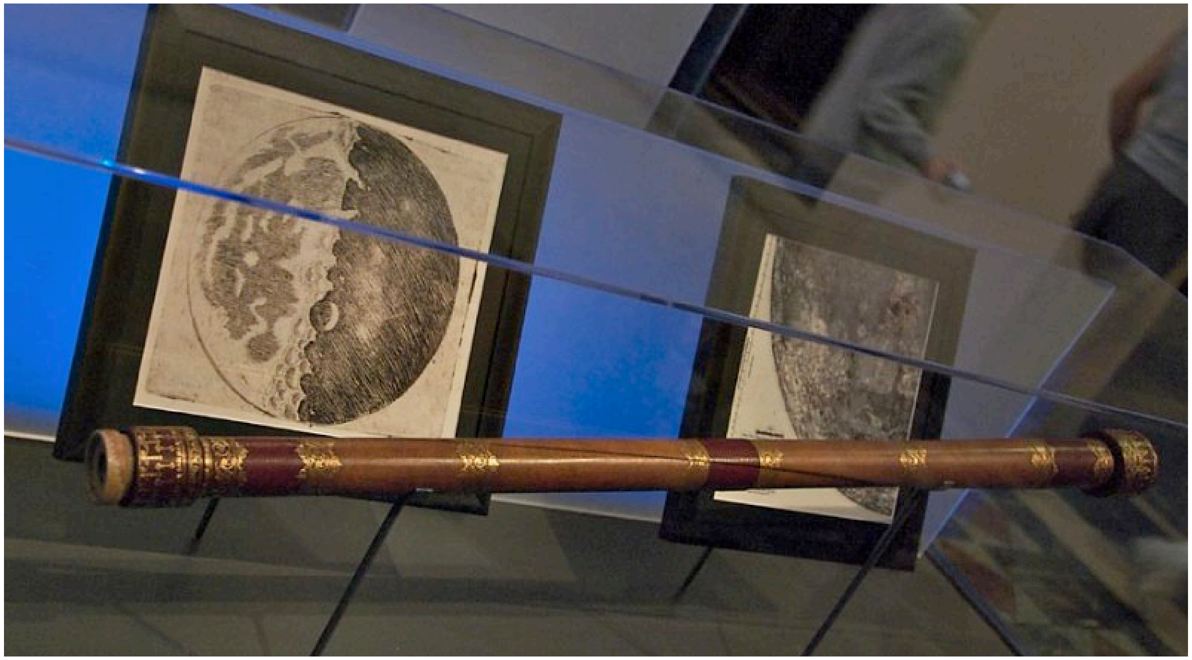
# The Eye

- The pupil is the opening in the center of the iris.
- The size of the pupil determines the amount of light that enters the eye.
- The pupil size ranges from only 3-8 millimeters.
- The small size of the pupil limits the amount of light that can enter the eye, maing it difficult to see faint or very distant astronomical objects.



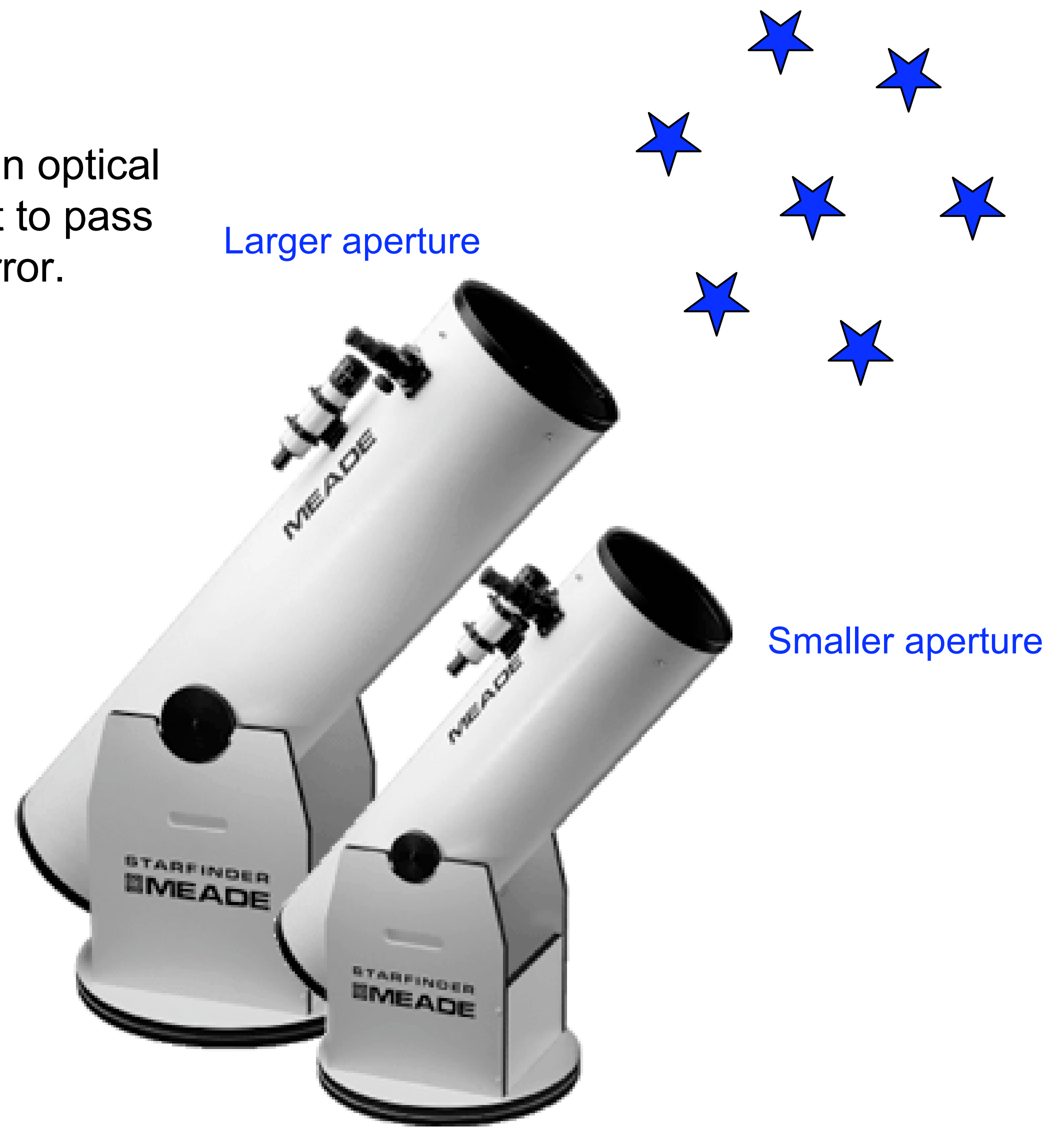
# 400 years ago: 1608

- The main purpose of a telescope is to gather as much light as possible and funnel it into your eye.
- Based on the telescope invented in the Netherlands in 1608, Galileo made a telescope with a 37 millimeter diameter aperture.



# Aperture

- Aperture is the opening in an optical instrument that permits light to pass through a lens or onto a mirror.



# 400 years ago: 1608

- The light gathering power (LGP) of a telescope is proportional to the *area* of the aperture:

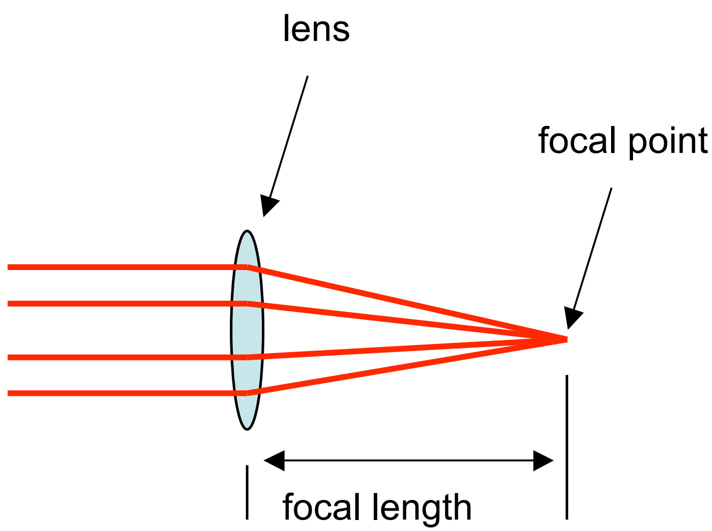
$$Area = \pi(radius)^2$$

- Therefore the light gathering power of Galileo's telescope was about 55 times that of the eye:

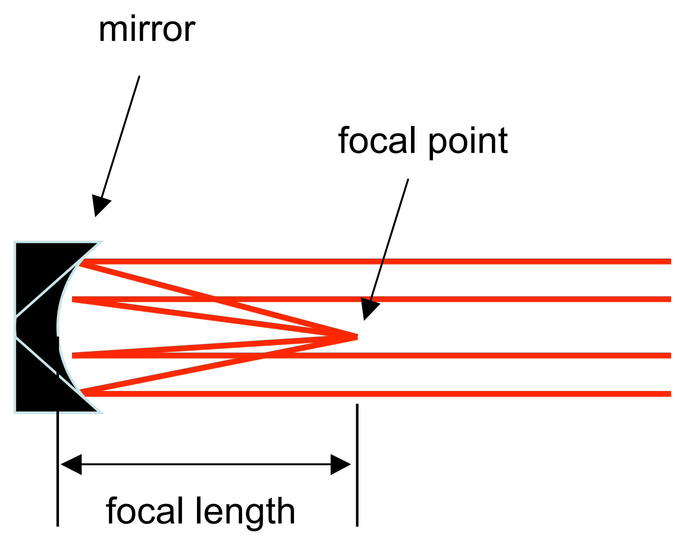
$$\frac{LGP_{Galileo's\ telescope}}{LGP_{eye}} = \frac{\pi(37mm/2)^2}{\pi(5mm/2)^2} \cong 55$$

Diameter = 37mm

# Classes of optical telescopes:
# Reflectors and refractors



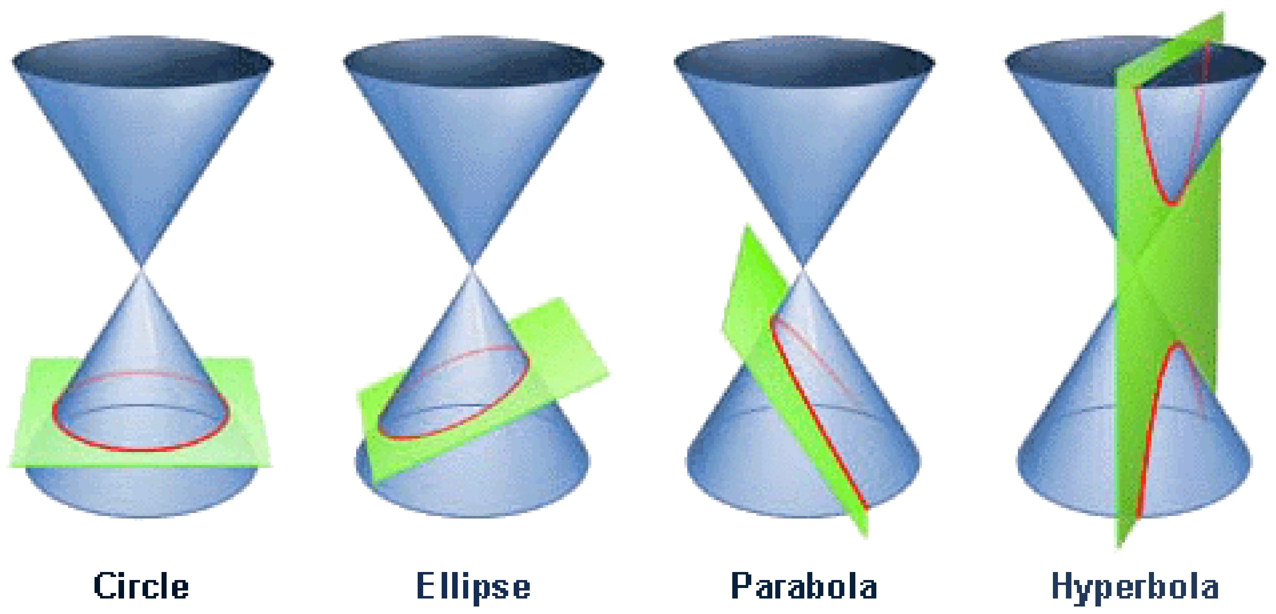

Refractors use lenses




Reflectors use mirrors

# Classes of lens and mirror shapes: Conic sections

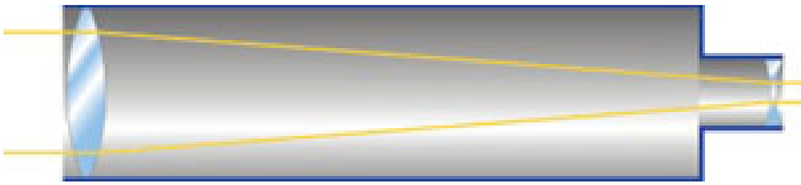
- Spherical (circular), parabolic, hyperbolic, and ellipsoidal describe the shape of a lens or mirror.



# Refracting telescopes

- Galileo's telescope was a refractor that used a spherical lens.

- The images he saw were imperfect because of aberrations caused by the spherical lens.



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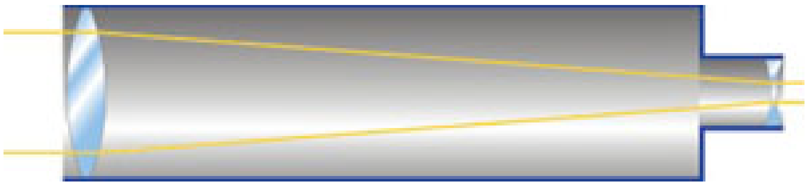
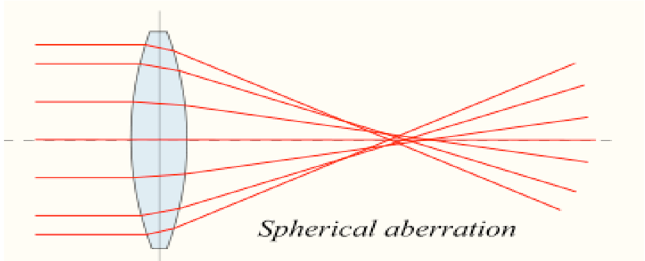
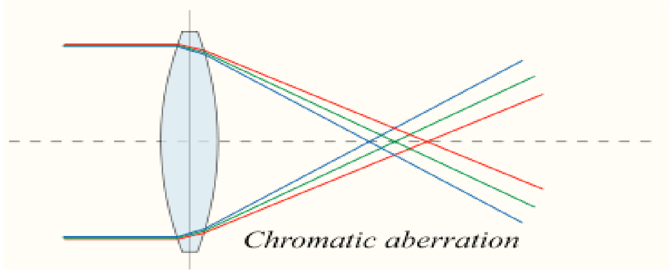


- The images he saw were imperfect because of aberrations caused by the spherical lens.

- Spherical aberration occurs because the spherical shape of the primary lens causes light at different distances from the optical axis to be focused at different distances.



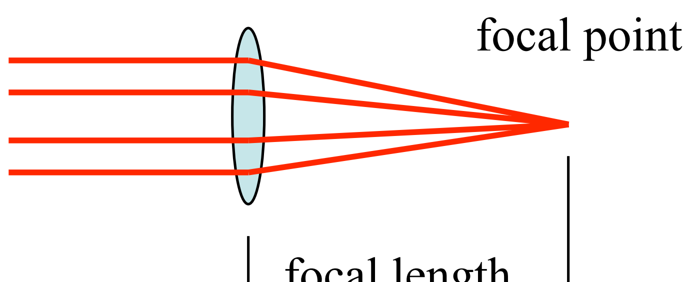

- Chromatic (color) aberration occurs because the index of refraction of a lens is a function of wavelength.



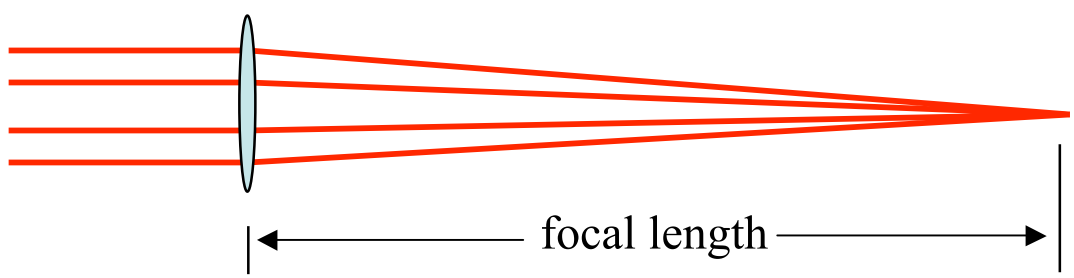
# Refracting telescopes

- Could get rid of spherical aberration by grinding a parabolic surface.
  - But spherically shaped lenses are much easier to make.

- Try to make spherical lens very thin so its spherical surface approximates a parabola.
  -




  - But that results in very long telescope.



# Refracting telescopes

- The world's largest refracting telescope is 19.3 meters (~63 feet) long!

- The ultimate size of refractors is limited by

  - Flexures imposed by the weight of the lenses

  - Absorption of light by massive lenses

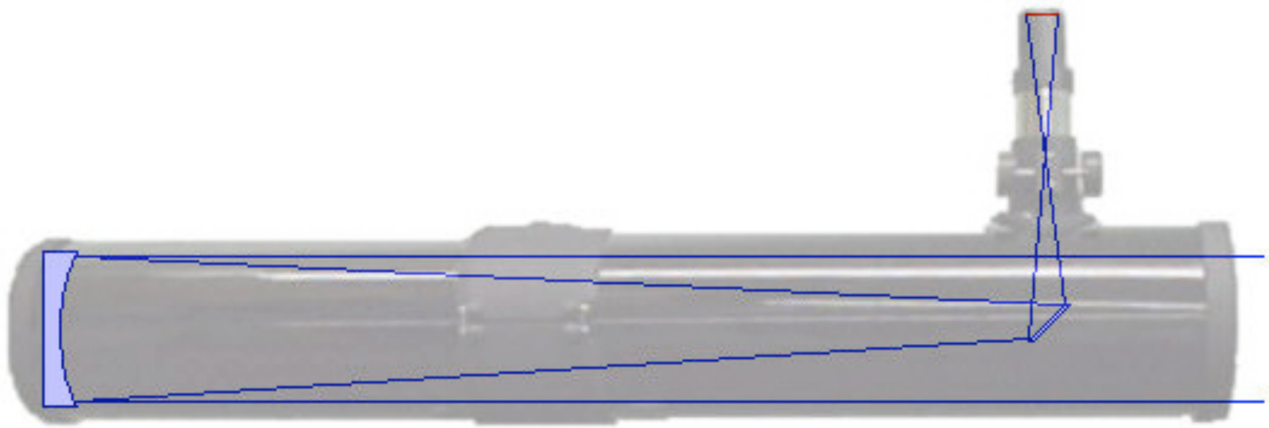
  - Unwanted refractions by large lenses

*A person!*

Yerkes
Williams Bay, WI

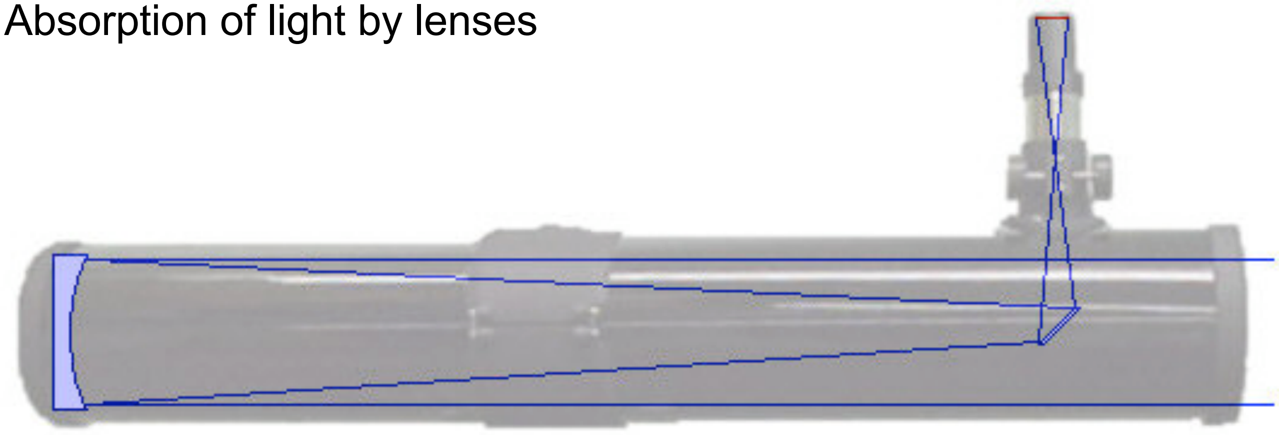
# Mirrors to the rescue!

- Newton replaced the lens with a mirror to eliminate chromatic aberration of lenses.



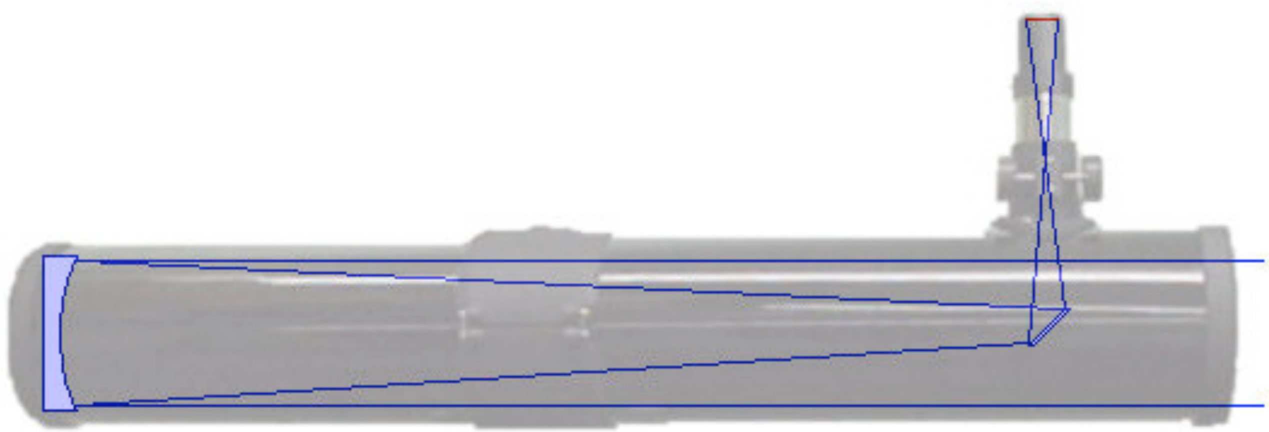
# Mirrors to the rescue!

- Mirrors overcome 4 of the 5 problems of refractors:
  - Chromatic aberration
  - Flexure from heavy lenses
  - Unwanted refractions
  - Absorption of light by lenses



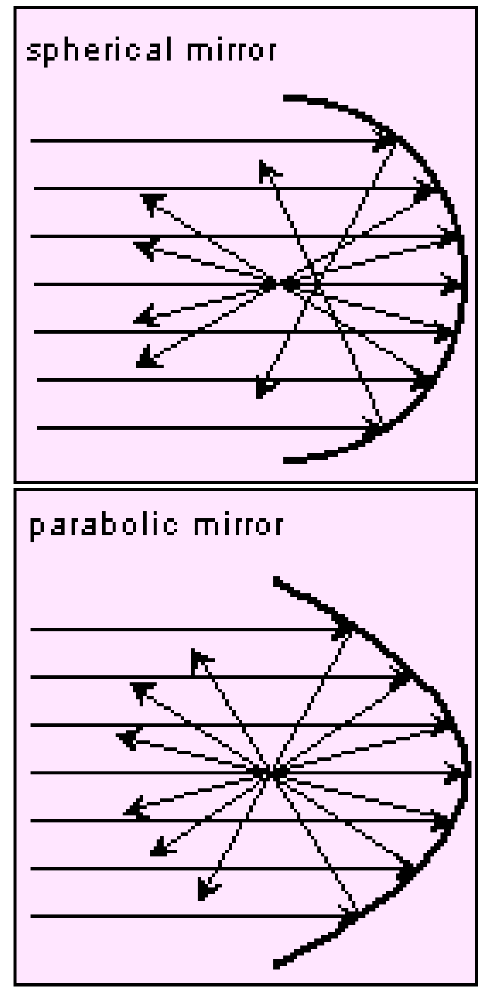
# Mirrors to the rescue!

- But mirrors can still have spherical aberration.



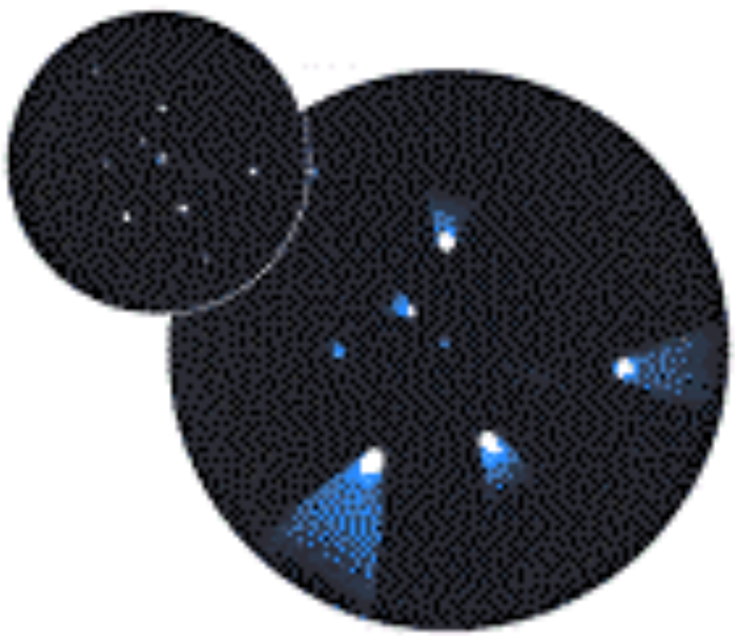
# One solution

- Use a parabolic mirror instead of a spherical mirror.
- With a perfect parabolic mirror, all rays are focussed to the same point, so there is no spherical aberration.



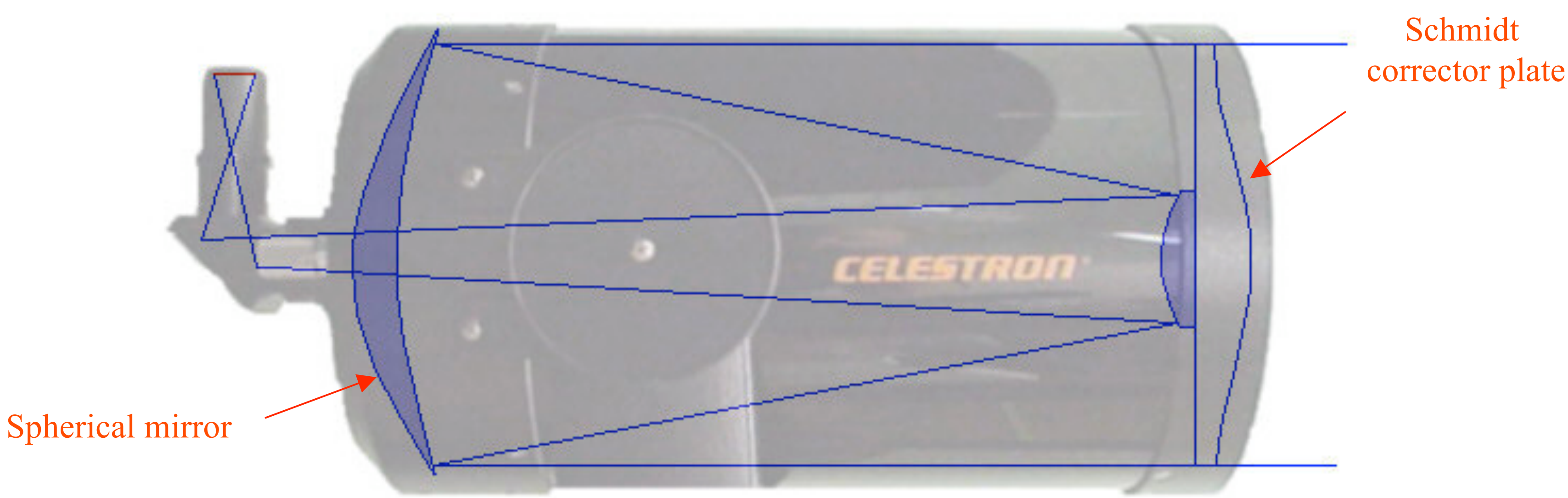
# Coma

- However, a parabolic mirror creates coma (coma = comet-like).



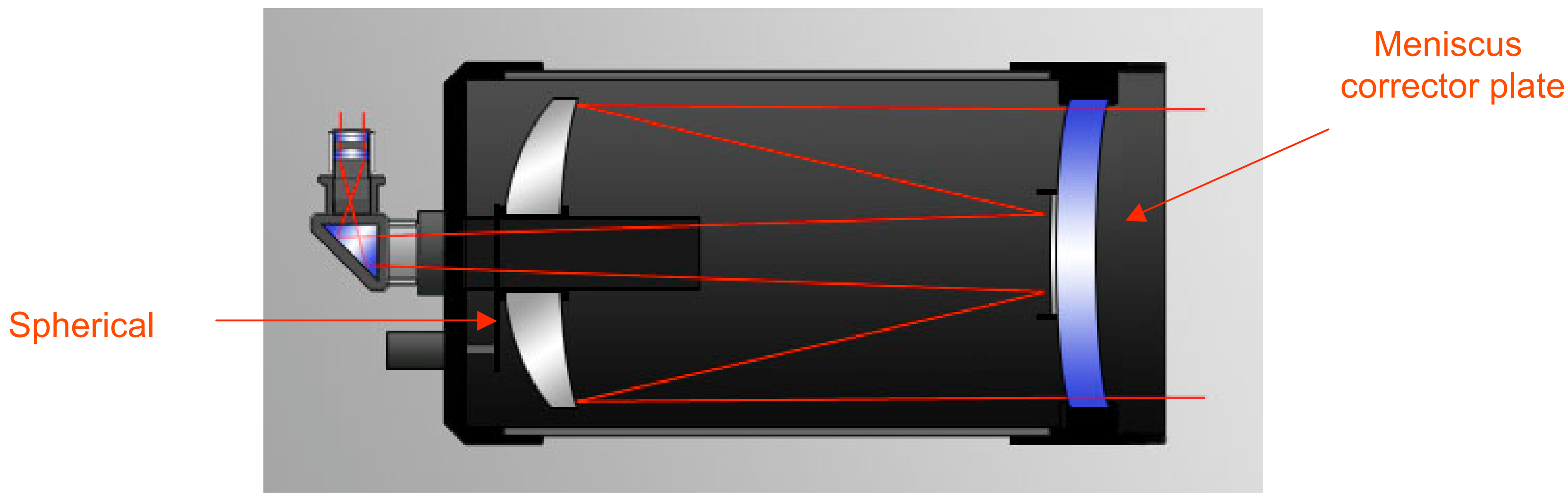
# Another solution: Schmidt-Cassegrain

- Uses a spherical mirror (instead of parabolic) to minimize coma
- Uses Schmidt corrector plate to correct for spherical aberration.



# Another solution: Maksutov-Cassegrain (Mak)

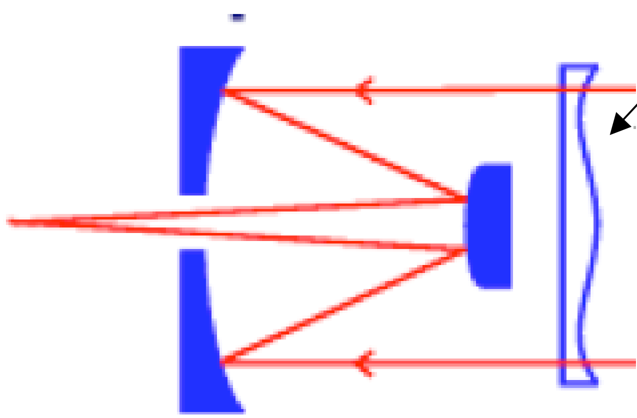
- Still use a spherical mirror to minimize coma.
- Maks use a less-expensive meniscus corrector, a highly curved spherical lens, to correct for spherical aberration.



# Correctors

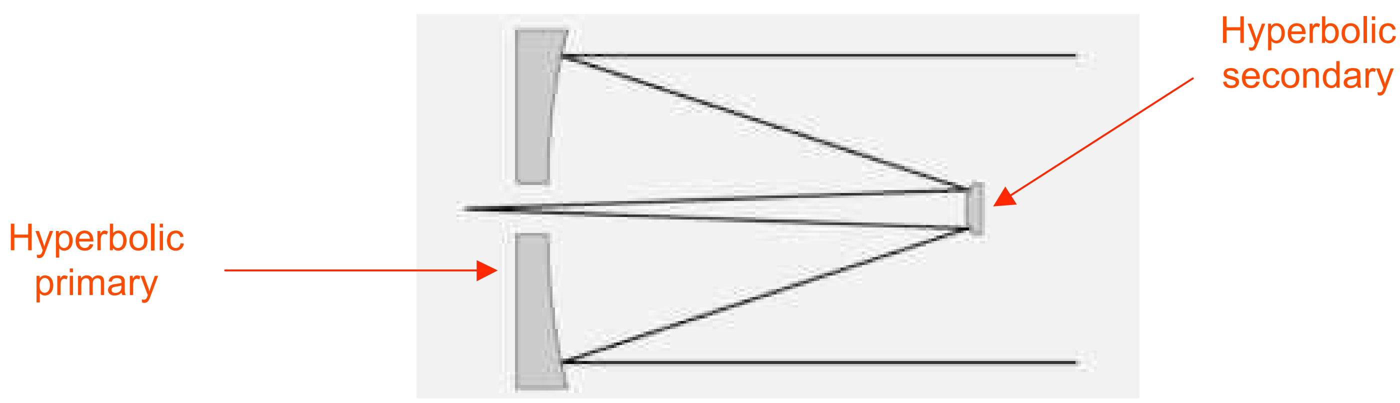
- Since correctors are lenses, don't they reintroduce chromatic aberration, the thing we were getting rid of by using mirrors?

- The amount of chromatic aberration is small and can be minimized by careful design of the shape, as the location of the "dip" in the Schmidt corrector plate and the thickness of the Mak correctors.



# Another solution: Ritchey-Chretien

- Many professional telescopes, including the Hubble Space Telescope, are of the Ritchey-Chretien (RCT) design.
- The RCT telescope is designed to eliminate coma as well as spherical aberration, thus providing a relatively large field of view.
- It has a hyperbolic primary mirror and a hyperbolic secondary mirror.



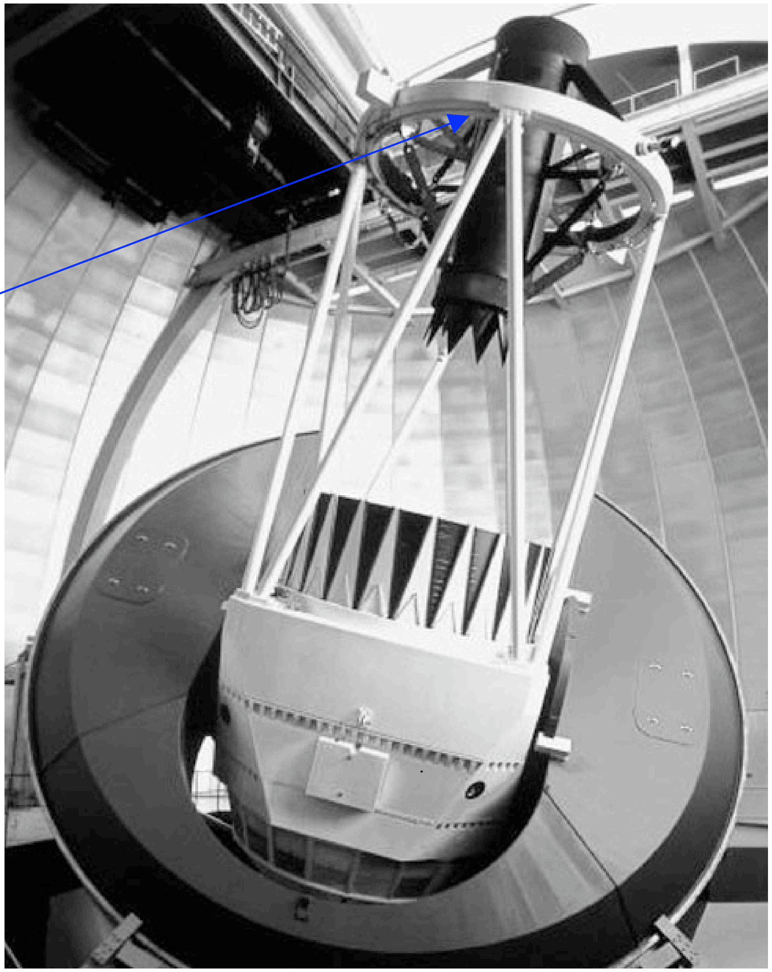
# Professional telescopes also have correcting lenses

- Dark Energy Survey:
  Goal: Learn why the universe seems to be expanding *faster* and *faster*.

- Build a new 500 Megapixel camera and wide field corrector to be used on the 4-meter Blanco telescope at Cerro Tololo Inter-American Observatory in Chile.

# Professional telescopes also have correcting lenses

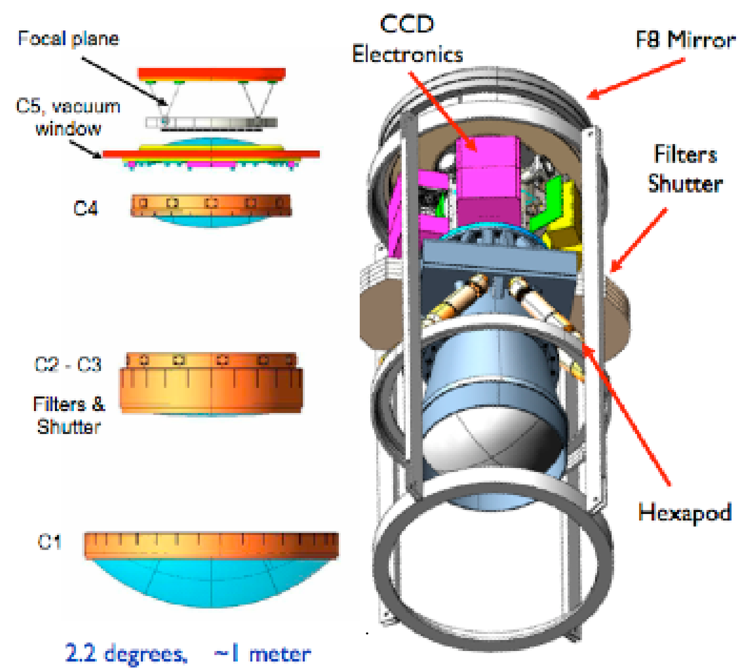
- Although the Blanco telescope has a hyperbolic primary, which helps eliminate spherical aberration and coma, the Dark Energy Survey requires such a large field of view (2.2 degrees) that a corrector is needed.



Blanco Telescope

# Professional telescopes also have correcting lenses

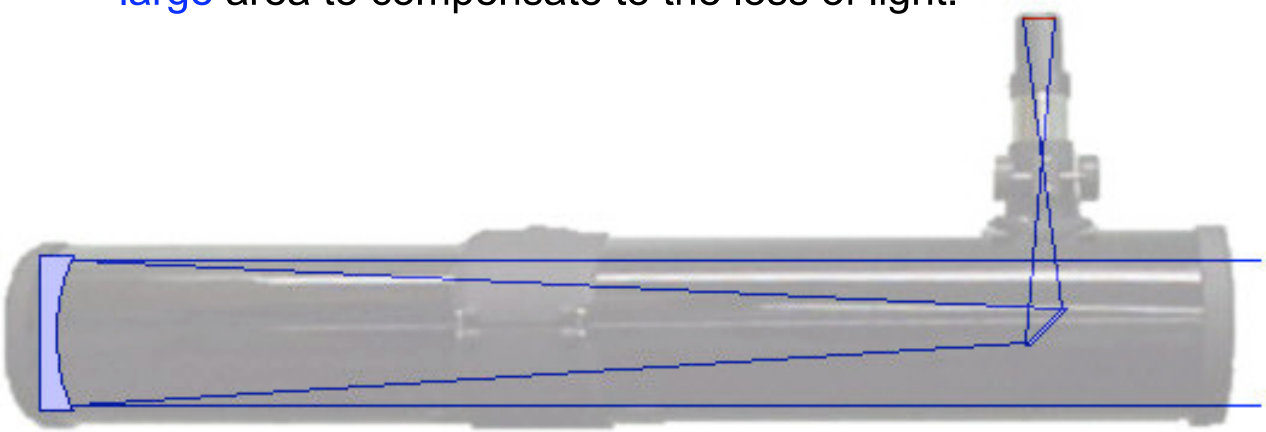
- The corrector is comprised of 5 lenses, each uniquely shaped to correct for a variety of aberrations.




Blanco corrector

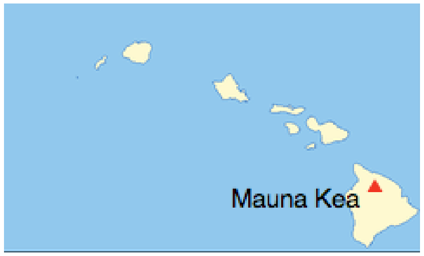
# Mirrors to the rescue?

- But reflectors present a new problem:
  - The secondary mirror of a reflector blocks some incoming light.
  - Prevents about 10% of light from reaching the primary mirror.
  - This problem is addressed by constructing primary mirrors with sufficiently large area to compensate to the loss of light.

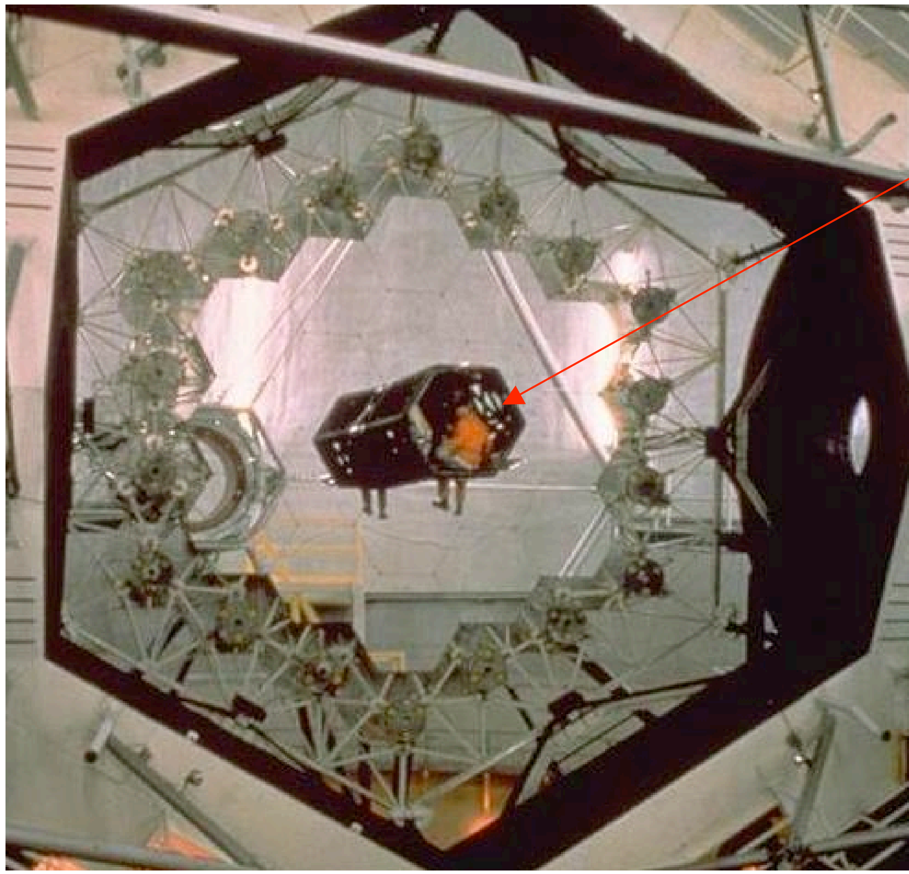


# Professional telescope mirrors are huge

- The Keck I and Keck II are located on Mauna Kea, Hawaii
- Each has a 10 meter mirror




# Large



*A person!*

10 meter Keck primary mirror

# Larger

- Gran Telescopio Canarias (GTC) is a 10.4 meter reflecting telescope in Canary Islands.

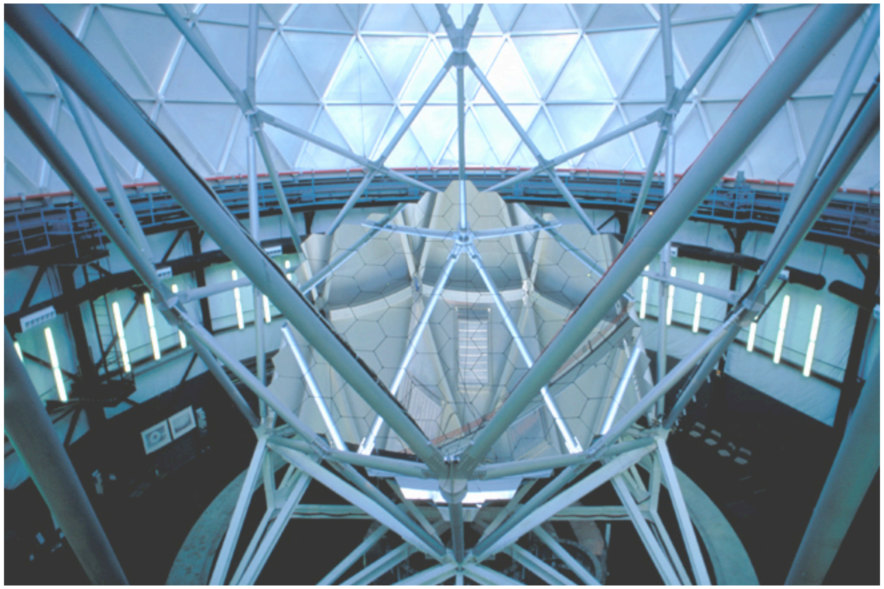
- The light gathering power of the GTC amounts to about 4 million human eyes!

$$\frac{LGP_{GTC}}{LGP_{eye}} = \frac{\pi(10,400mm/2)^2}{\pi(5mm/2)^2} \cong 4,326,400$$

10.4 meter GTC mirror

# Largest!

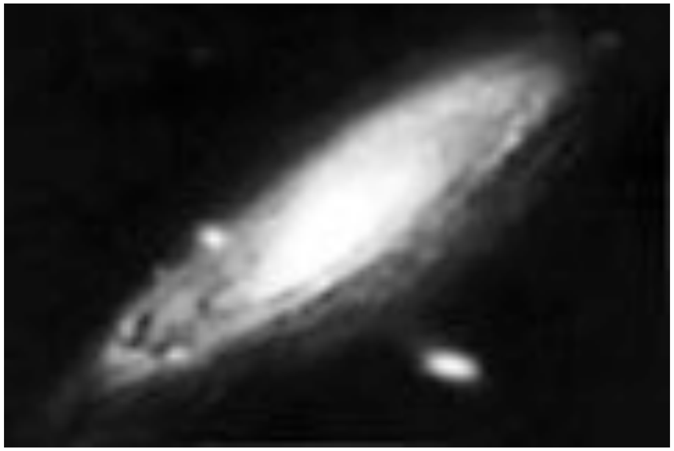
- The largest optical telescope is South Africa Large Telescope (SALT).
- 11 meters in diameter
- And today people are working on even larger telescopes!



SALT 11 meter SALT mirror

# Resolution

- Larger telescopes have the nice ‘side effect’ of also providing higher resolution.
- Resolution is how fine a detail a telescope can see or how close together two objects (such as stars) can still be seen as two distinct objects.
- Resolution is proportional to $\dfrac{\text{wavelength of light observed}}{\text{diameter of telescope}}$



Low resolution

High resolution

# Seeing is Believing:

- What limits how much the naked eye can see?
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# Telescopes on Earth and in Space

- How have astronomers overcome the limitations imposed by the human eye?
  - Telescopes
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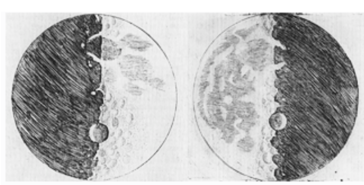
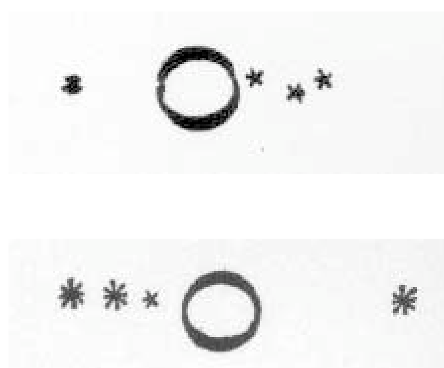
# Galileo

- Galileo was the first to use the telescope systematically to observe celestial objects and to record and publish his observations.
  - Observations were by eye
  - Observations were recorded manually
  - Galileo published his observations in a short treatise entitled *Sidereus Nincius* (*Starry Messenger*)

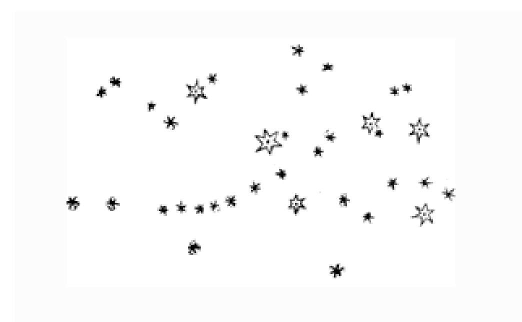


Moon



Jupiter’s moons

(referred to as Galilean moons)

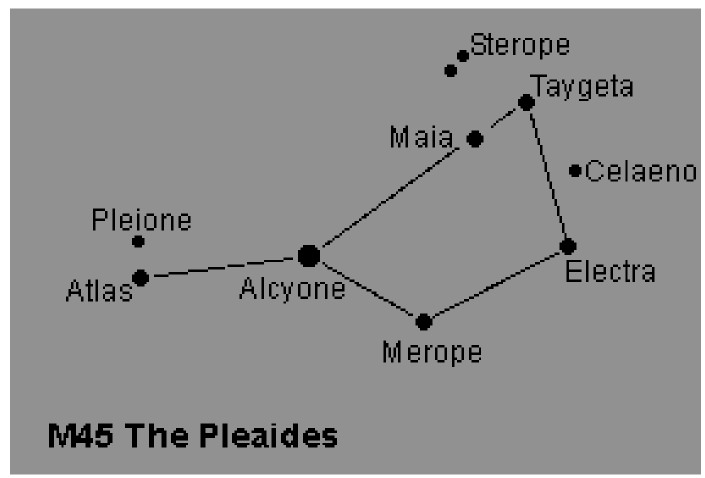


The Pleiades

Showing more stars than are visible to the unaided eye.

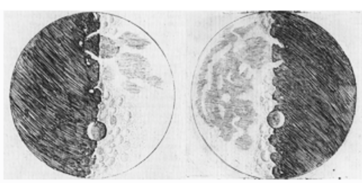
# Pleiades

- Subaru is the Japanese name for the Pleiades.

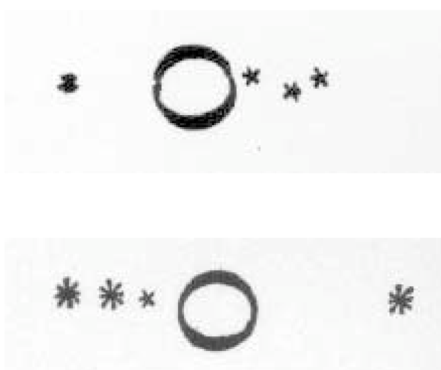


# Galileo

- Notice that the objects Galileo viewed were “nearby”.
- Even if he stared longer and longer into the telescope, he could not see fainter and fainter objects.
- This is because the eye “refreshes” every 50-100 ms.



Moon



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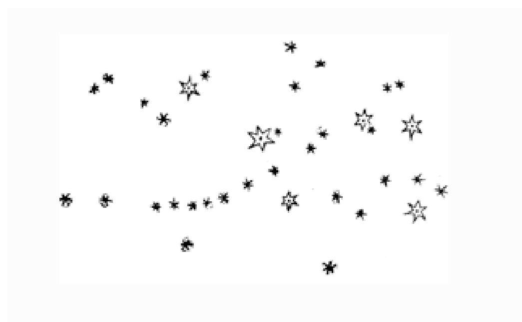

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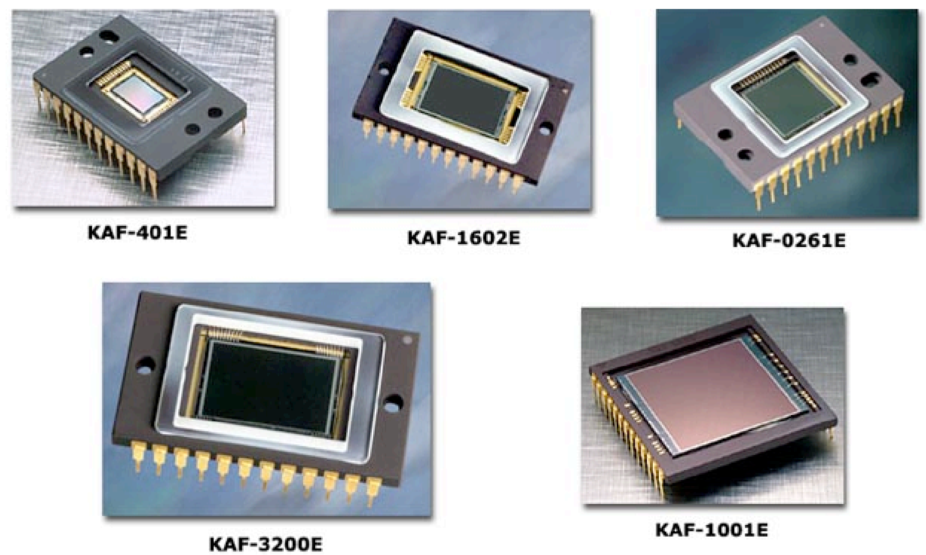
# Film rate

- Through experience in the early days of film, it was determined that a frame rate of less than 16 frames per second caused the mind to see flashing images.
- This is because persistence of vision depends on chemical transmission of nerve responses, and this biochemical process takes about 50-100 milliseconds.

# Photography and digital imaging

- However, photographic film and digital cameras CAN stare at the sky for a long time and store more and more light.
- Therefore, by replacing the human eye with cameras, we can detect fainter and more distant objects.




Chips used in digital cameras

# Hubble Ultra Deep Field

- The deepest image of the universe ever achieved by humankind: Hubble Ultra Deep Field.
- The HUDF is comprised of 800 exposures that amount to 11.3 days of exposure time.
- Can digitally add the 800 images.
- Result is an image of 10,000 galaxies which are much to faint and distant to be seen with the eye looking through the telescope.

Hubble Ultra Deep Field

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  - Telescopes
  - Detectors
  - Telescopes and cameras that can detect colors beyond those the eye can see

# Optical

- Galileo observations and the Hubble Deep Field only show us what things look like in the optical part of the spectrum: the light that the human eye can detect.

Hubble Ultra Deep Field

# Rainbows

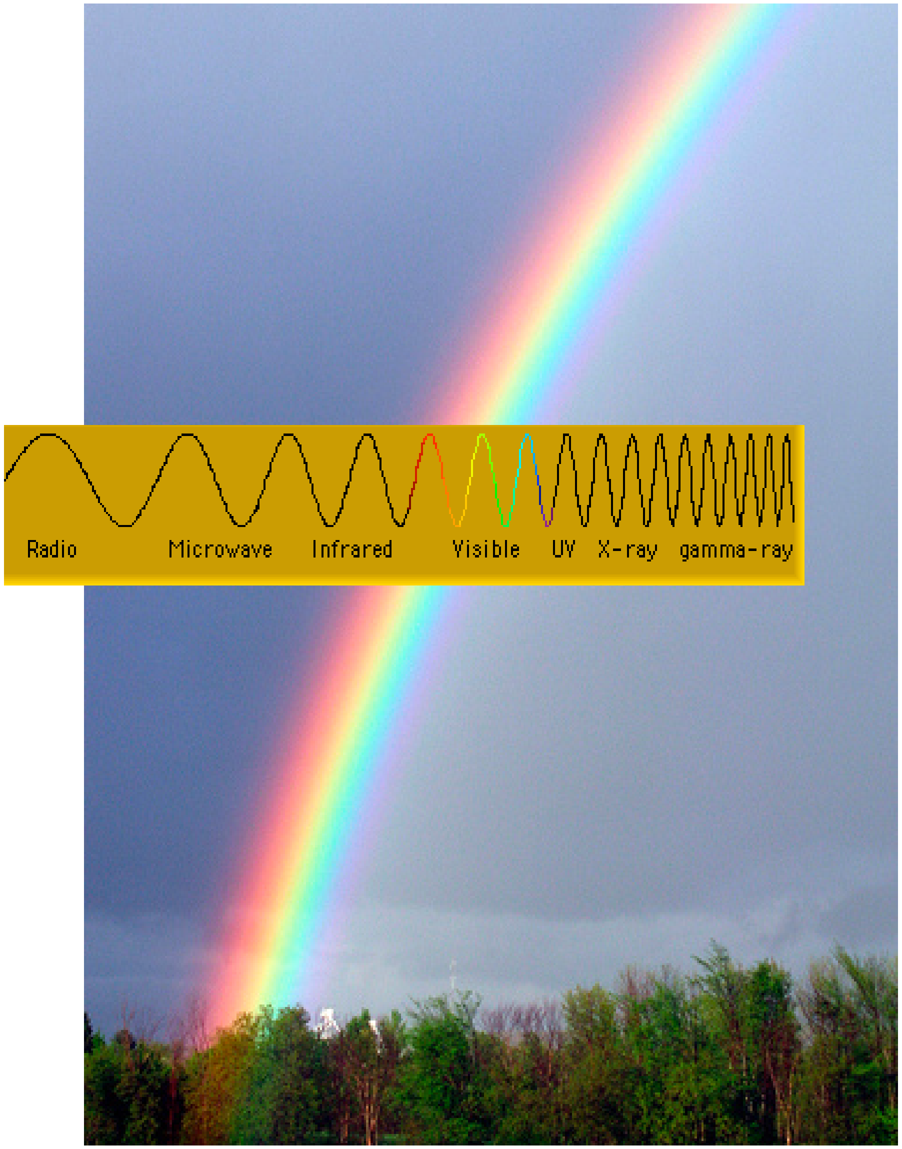
- But look at a rainbow…
- Each color transitions to the next, but when you get to either the red or the violet end, the rainbow seems to stop, or fade into nothing.
- Or does it just actually transition to colors that are invisible to our eyes?

# Rainbows

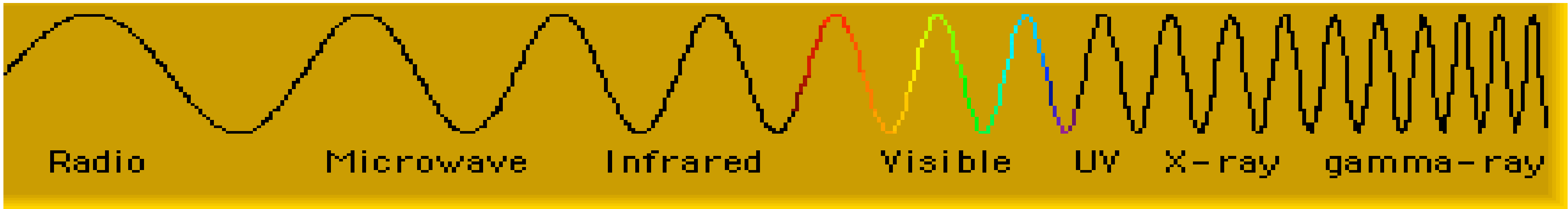
- If we put other detectors on either side of the rainbow, could we detect more ‘colors’?
- Yes.

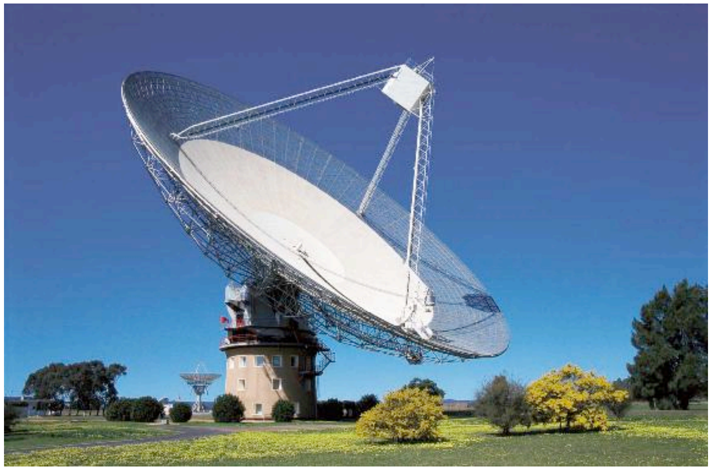
# Wavelength

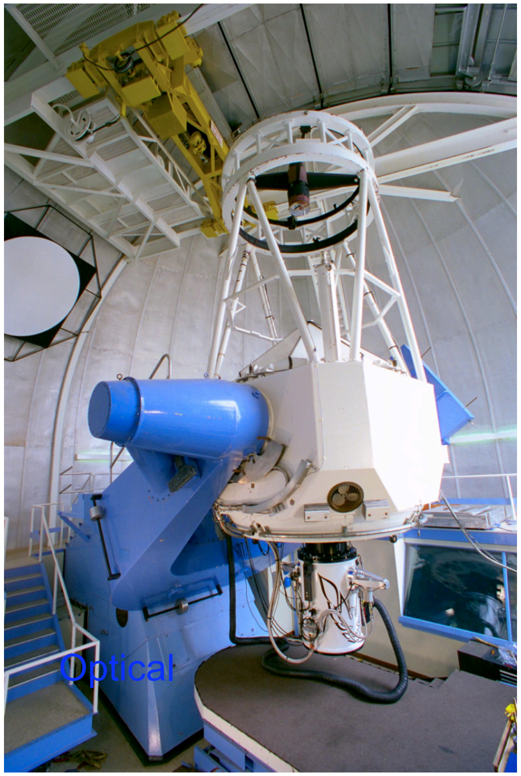
- The different 'colors' have different wavelengths.



# Different telescopes for different wavelengths

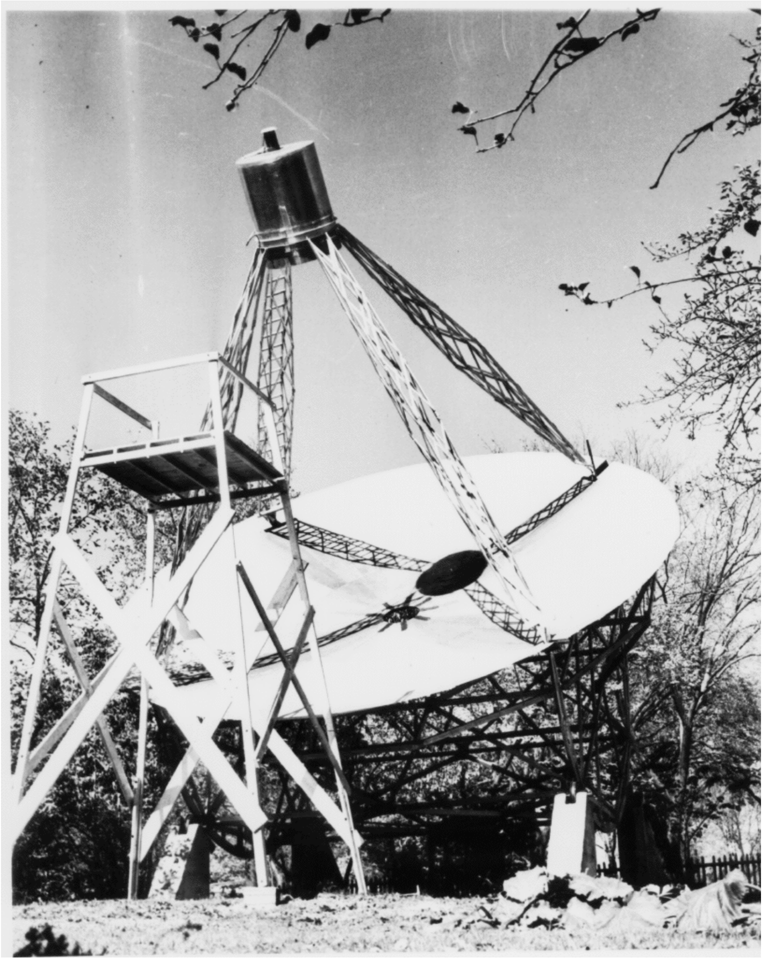





# Early radio telescope in Wheaton, Illinois

- Grote Reber built one of the first radio telescopes.
- He built it in his back yard in Wheaton, IL.

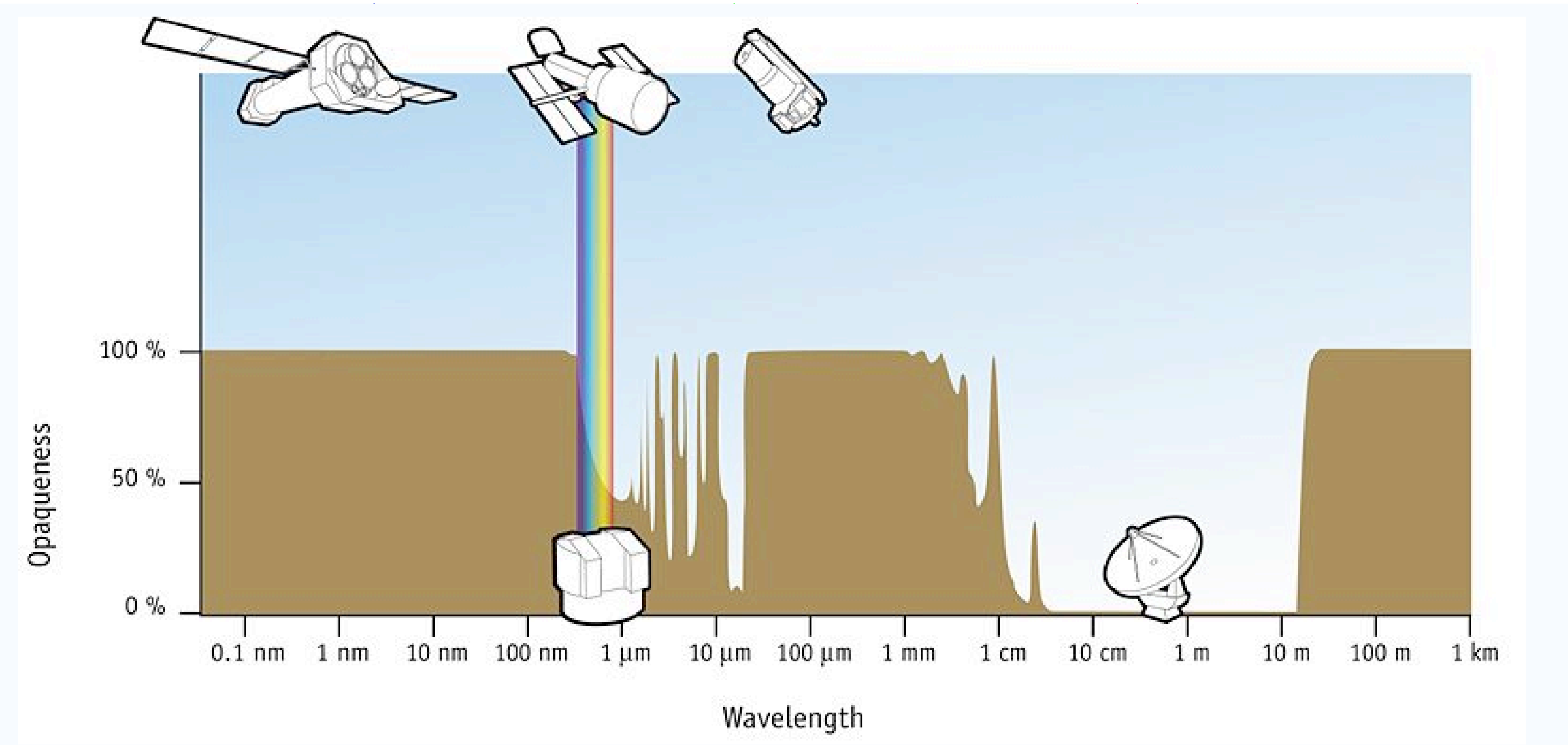


# Atmospheric windows

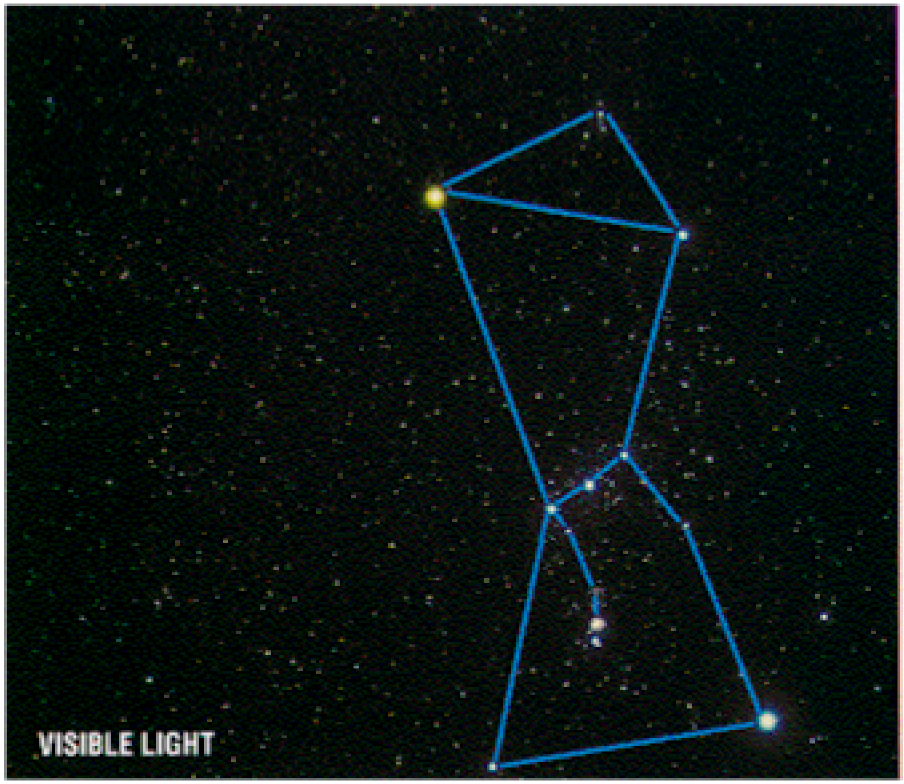
Ultraviolet
xrays, gamma rays

Infrared and
optical

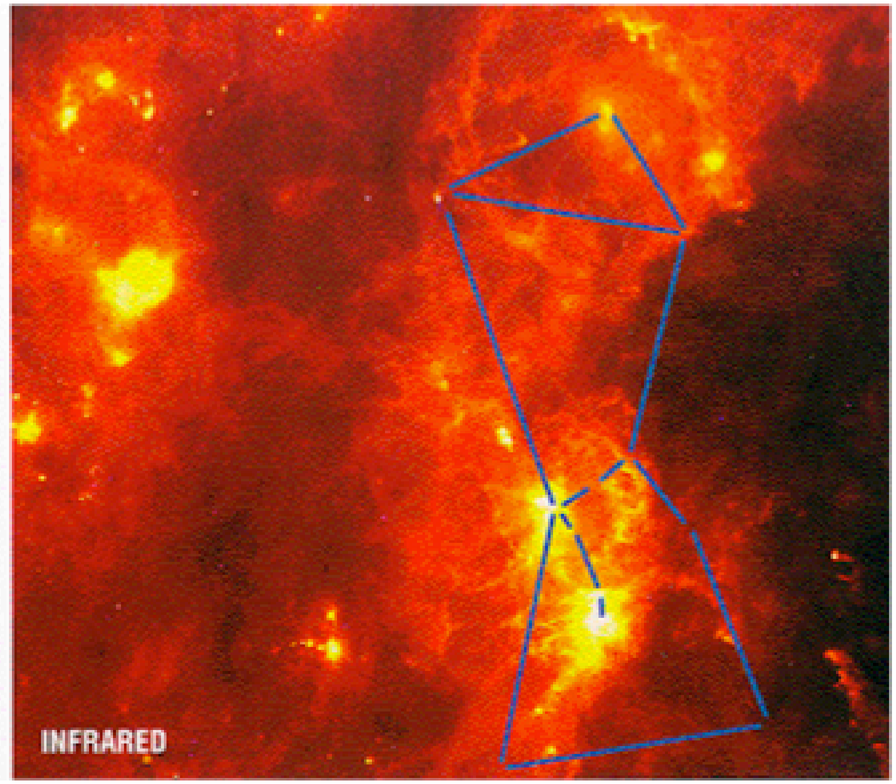
Radio,
millimeter,
sub-millimeter



# And the images look very different!



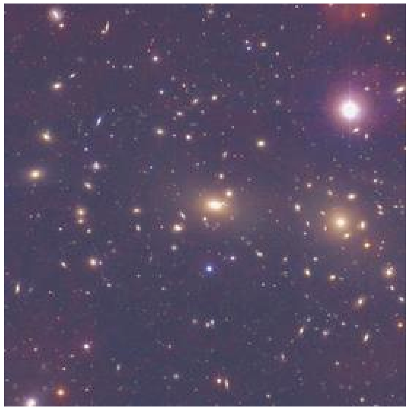

Orion Consellation



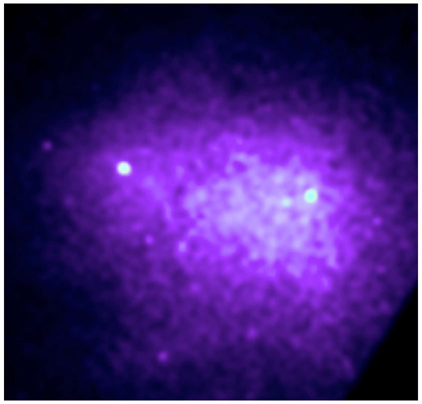

Orion Consellation

# And the images look very different!

- Coma is a cluster of galaxies.
- The galaxies themselves are seen in the optical image.
- The hot gas between the galaxies emits x-rays which are seen in the x-ray image.
- If we had only the optical image, we would have the wrong impression of the Coma cluster.



Coma cluster
Optical image



Coma cluster
X-ray image

# The Blindmen and the Elephant

by John Godfrey Saxe

It was six men of Hindustan

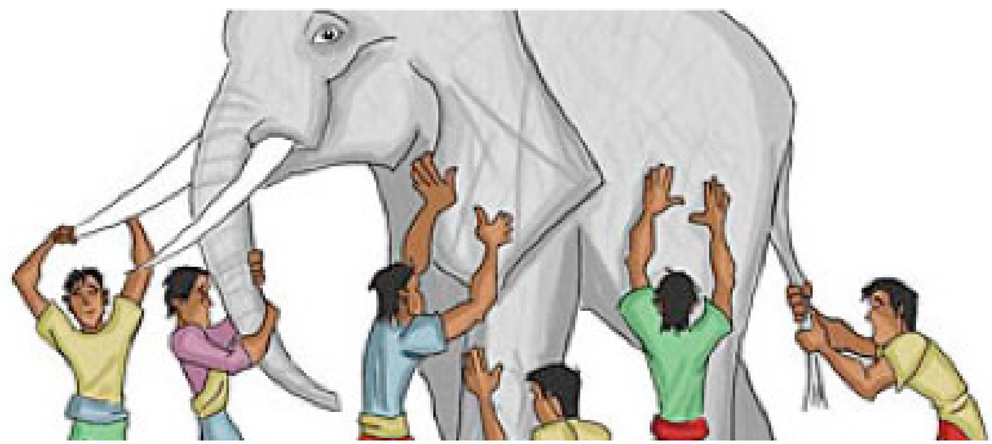
To learning much inclined,

Who went to see the Elephant

(Though all of them were blind)

That each by observation

Might satisfy the mind.



# The Blindmen and the Elephant

The First approached the Elephant

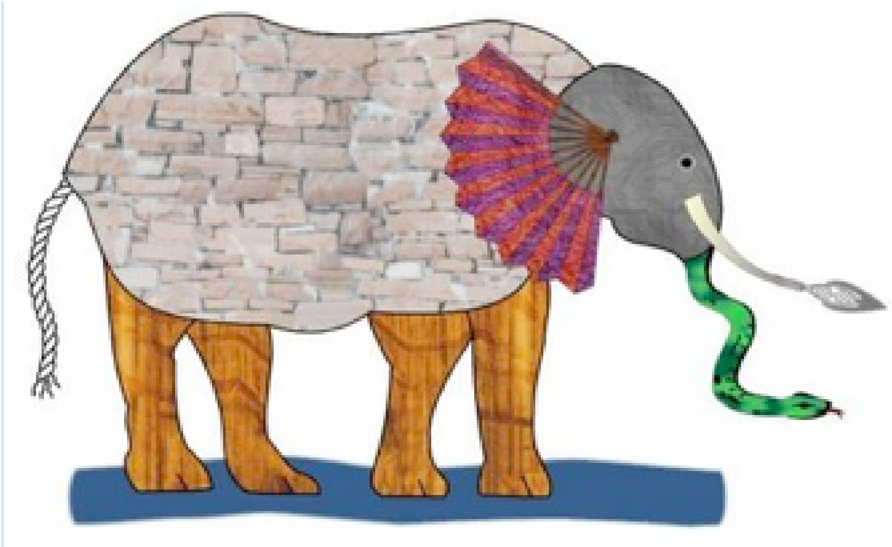
And happening to fall

Against his broad and sturdy side

At once began to bawl:

"Bless me, it seems the Elephant

Is very like a wall".



# The Blindmen and the Elephant

The Second, feeling of the tusk, Cried,

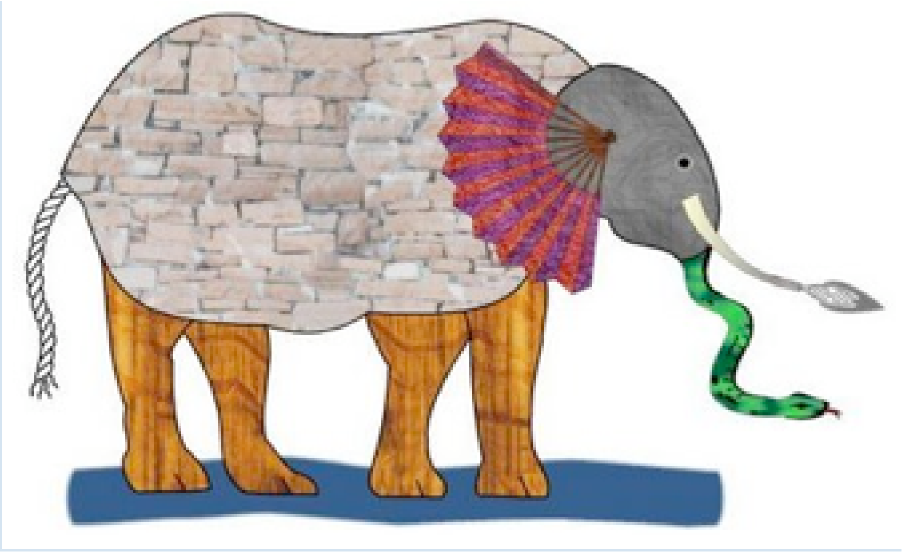
"Ho! what have we here

So very round and smooth and sharp?

To me 'tis mighty clear

This wonder of an Elephant

Is very like a spear!"



# The Blindmen and the Elephant

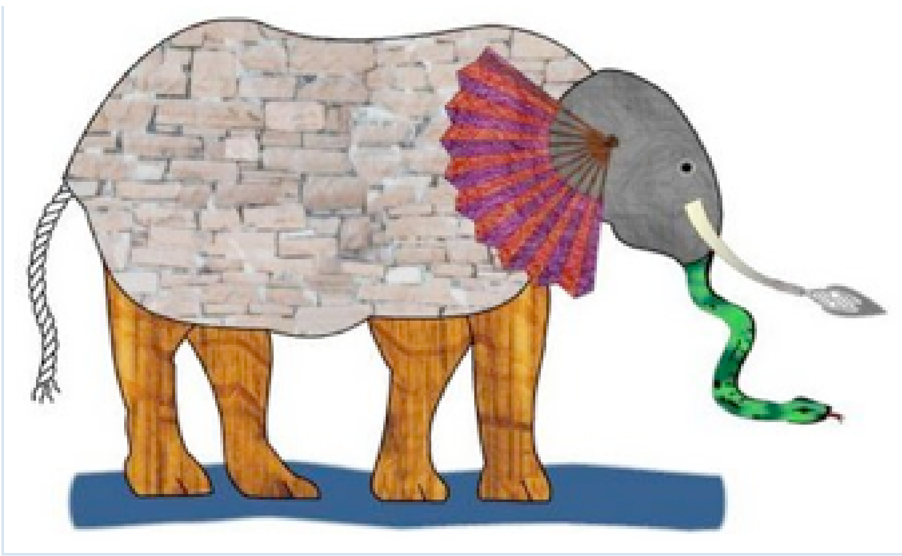
The Third approached the animal,

And happening to take the squirming
trunk within his hands,

Thus boldly up and spake:

"I see," quoth he, "the Elephant

Is very like a snake!"



# The Blindmen and the Elephant

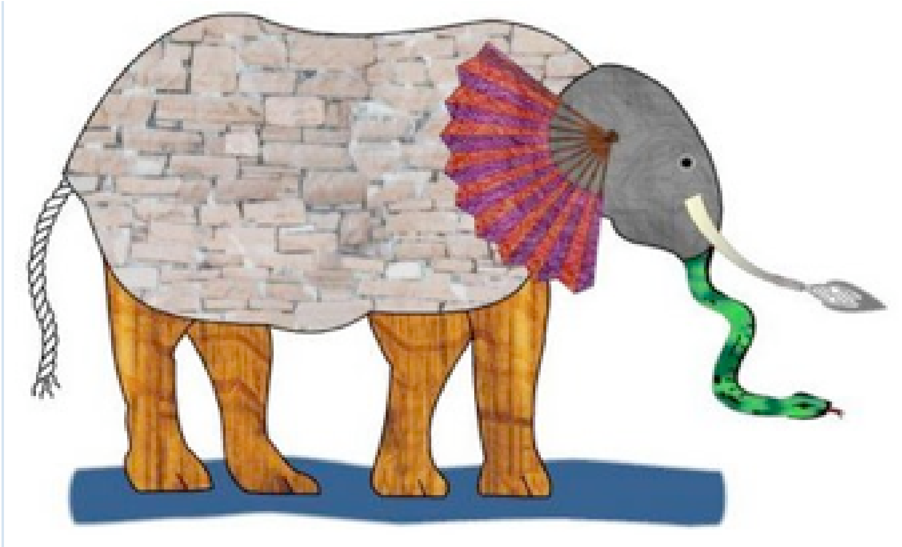
The Fourth reached out his eager
hand,

And felt about the knee.

"What most this wondrous beast is
like is mighty plain," quoth he,

"'Tis clear enough the Elephant

Is very like a tree!"



# The Blindmen and the Elephant

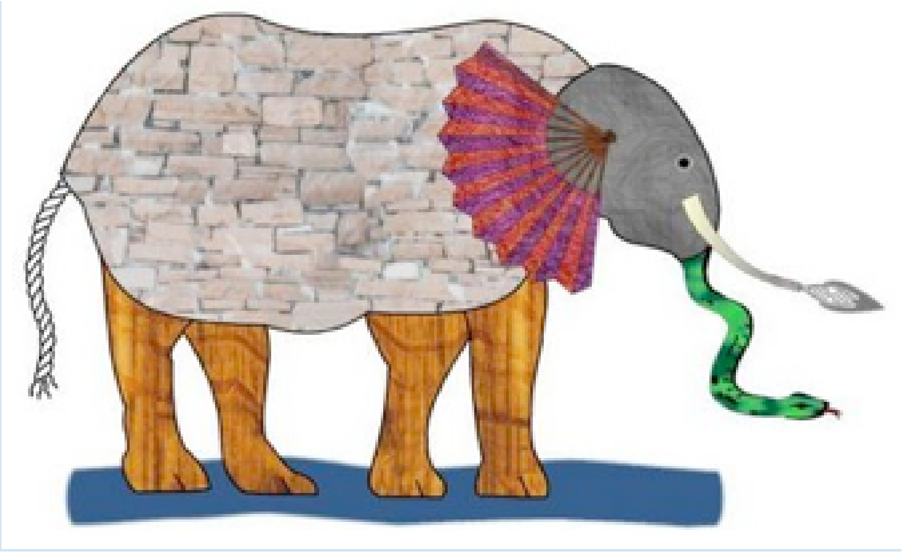
The Fifth, who chanced to touch the ear,

Said: "E'en the blindest man can tell what this resembles most;

Deny the fact who can,

This marvel of an Elephant

Is very like a fan!"



# The Blindmen and the Elephant

The Sixth no sooner had begun

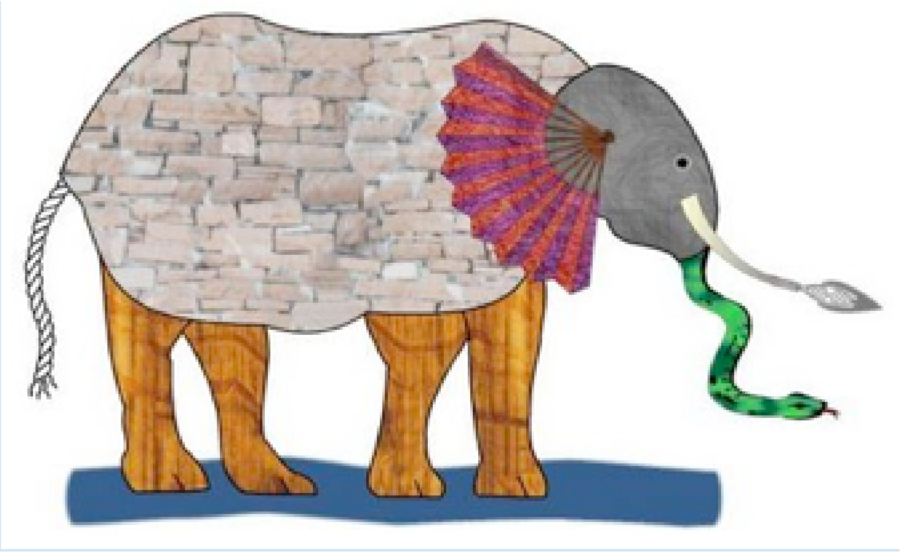
About the beast to grope,

Then, seizing on the swinging tail that

fell within his scope,

"I see," quoth he, "the Elephant

Is very like a rope!"



# The Blindmen and the Elephant

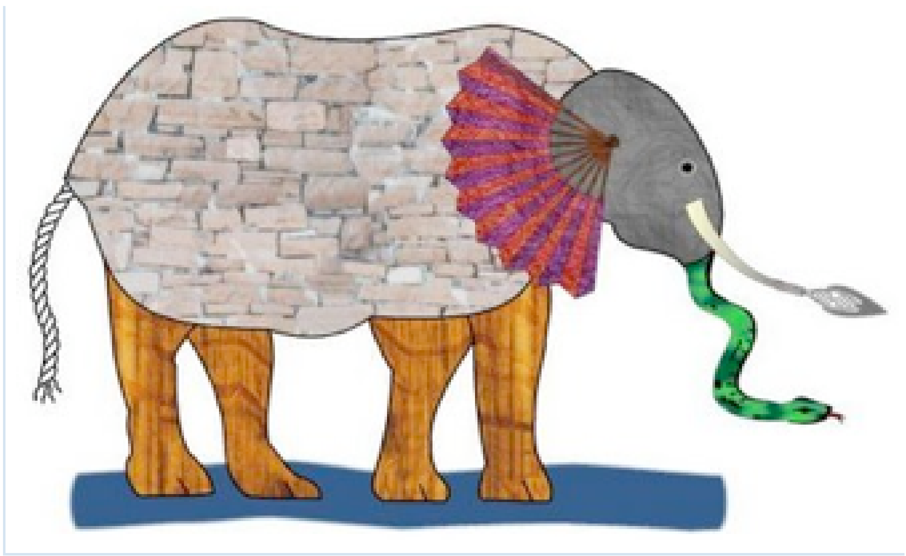
And so these men of Indostan

Disputed loud and long, Each in his own opinion

Exceeding stiff and strong,

Though each was partly in the right,

And all were in the wrong!



# The Blindmen and the Elephant

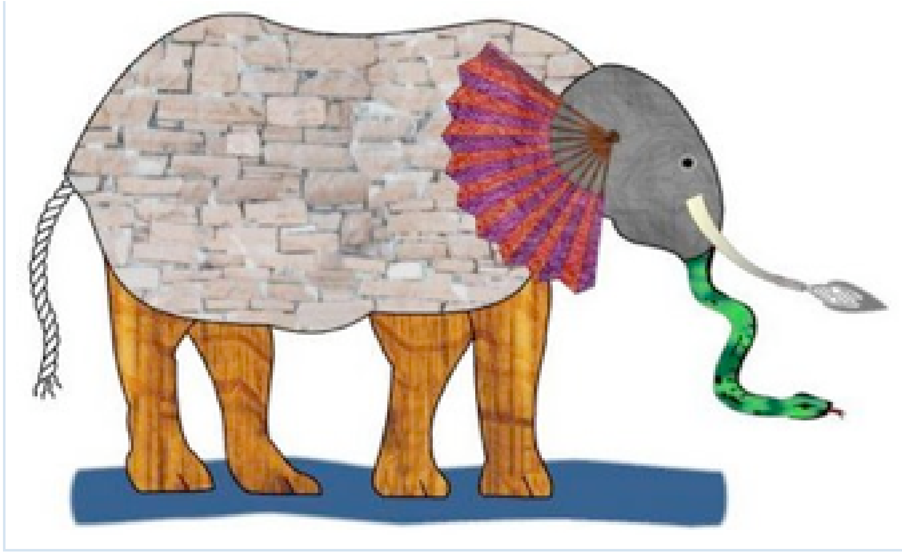
If we let our telescopes

Observe in only one wavelength, even
for very long,

Though we'd be partly in the right,

We'd be missing the most important

words in the song....



# The Future's So Bright, I Gotta Wear Shades

by Timbuk 3